Interhemispheric Comparison of the Development of the Stratospheric Polar Vortex during Vail: a 3-Dimensional Perspective for 1991-1992

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Abstract. The development of the stratospheric polar vortex during fall and early winter in the Northern Hemisphere (NH) during 1991-1992, and the Southern Hemisphere (S1 I) during 1992 is examined using National Meteorological Center data, Compared to the NH, the polar vortex in the SH developed with less variability y on short t imc scales, deepened more rapidly and continued to expand well into winter. Daily minimum temperatures in the lower stratosphere occurred at equivalent seasonal elates in both hemispheres, but fell below the condensation temperatures of polar stratospheric clouds (PSCs) much earlier in the S11, The region where vortex air was cold enough to form PSCs had a greater vertical extent in the S11, where it attained a maximum volume ≈3 times that in the N]]. That part of this region in sunlight covered approximately twice the area in the S11 that it did in the NH. These interhemispheric meteorological differences are generally consistent with the chlorine monoxide distributions observed by the Microwave Limb Sounder on the Upper Atmosphere Research Satellite.

Introduction

During the Northern Hemisphere (N11) winter of 1991-1992, elevated values of chlorine monoxide (C1O, an active form of chlorine which destroys ozone) were observed in the polar lower stratosphere during late December and early January by the Microwave Limb Sounder (MLS) onboard the Upper Atmosphere Research Satellite (UARS) [Waters et al., 1993]. Elevated values of ClO were observed in the Southern Hemisphere (SH) by the UARS MLS as early as the beginning of June 1992. Current photochemical theory suggests that the formation of regions of high ClO in the lower stratosphere depends upon the existence of temperatures low enough for polar stratospheric clouds (PSCs) to form in or near areas that receive sunlight [e.g., Solomon, 1990]. The temperature at which PSCs form in the lower polar stratosphere depends principally on the cloud composition. Type II (mainly water-ice) particles condense at temperatures $<$ 188 K, while aircraft measurements have detected significant numbers of Type I (possibly nitric acid trihydrate, or NAT) particles in air with temperatures $\leq$ 195 K in the Antarctic [Fahey et al., 1989] and $\leq$ 192 K in the Arctic [Dye et al., 1992; Kawa et al., 1992].

To help understand the meteorological factors affecting the initial activation of chlorine in early winter in both hemispheres as observed by UARS MLS, and to describe the wintertime formation of the stratospheric polar vortex, we contrast the development of the polar vortex during fall and early winter 1991-1992 in the NH and 1992 in the SH.

Data and Analysis

The data are daily analyses of geopotential height and temperature provided through the UARS Project by the National Meteorological Center (NMC). These data are provided on 65 x 65 polar stereographic grids for each hemisphere and are interpolated from the 18 standard NMC pressure levels to a UARS pressure grid, defined by $p_n = (1000\ \text{hPa})\ e^{-n/6}$, $n = 0, 1, 2, \ldots,$ for comparisons with UARS data. For isentropic analyses, fields are interpolated using NMC temperatures to isentropic surfaces near these standard UARS pressure levels.

Horizontal winds are calculated from NMC geopotential height data using the technique described by Randel (1 987), expressed in polar stereographic coordinates. The Rossby-Ertel potential vorticity,

$$Q = - g (\zeta_0 + f) \frac{\partial \theta}{\partial p},$$

with gravity g, Coriolis parameter f, pressure p, potential temperature θ, and ζ_0, the component of relative vorticity orthogonal to the θ surface, is calculated from wind and temperature each day using an algorithm similar to that of Newman et al. (1989).

Results

Area integrals of Q can describe the evolution of the polar vortex on isentropic surfaces [Butchart and Remsberg, 1986; O'Neill and Pope, 1990]. Figure 1 shows area integrals on the 840 K isentropic surface (near 10 hPa) in the mid-stratosphere, and the 520 K surface (near 50 hPa) in the lower stratosphere. The times examined are 1 October 1991 through 31 January 1992 in the NH and the seasonally equivalent time period (i.e., a shift of 6 months) 1 April through 1 August 1992 in the SH. The lower level is near the altitude of maximum observed ClO concentration and, in the SH, of severe ozone depletion during late southern winter and spring [Waters et al., 1993].

As illustrated in Fig. 1, the wintertime polar vortices developed initially at nearly the same seasonal date at the upper level, while vortex development in the NH lagged its counterpart in the SH at the lower level. By middle to late fall, when the vortices were well established, the SH vortex was deepening more rapidly, as seen in the date of appearance in Fig. 1 of contours with $|Q| \geq 6\,(0.6) \times 10^{-4}$ K $m^2 kg^{-1} s^{-1}$ at 840 K (520 K). Furthermore, the polar vortex continued to grow in area in the SH until near the end of

July, while the NH vortex did not increase after the first week of December at 840 K nor after the end of December at 520 K. In the NH the vortex shrank abruptly at 840 K during the latter part of January, due to a strong minor stratospheric sudden warming that took place during that time [Naujokat et al., 1992]. In addition, the development of the polar vortex in the NH was much more variable on time scales of a few days to a week.

The $\pm 0.4 \times 10^{-4}$ K $m^2 kg^{-1} s^{-1}$ contours of Q are used to define the polar vortex "edge" at 520 K; this contour was near the equatorward side of the region of strong gradients of Q that tend to isolate the polar vortex. Using this definition, Fig. 2 shows the daily minimum temperature inside the polar vortex at 520 K for equivalent seasonal periods in the NH and SH. The more rapid decrease within the SH polar vortex is apparent and is reflected in the earlier appearance in the SH of temperatures low enough to form PSCs and in the much ($\approx$10 K) lower daily minimum temperatures by late fall. As will be shown later, temperatures were somewhat colder just above the 520 K level, with daily minimum temperatures < 195 K appearing in the NH around 1 December 1991, and in the SH around 10 May 1992 (seasonally equivalent to 10 November, 1991 in the NH). This is consistent with the elevated ClO values that were observed earlier in the SH fall than in the NH by the UARS MLS [Waters et al., 1993].

At the end of January in the NH and of July in the SH, temperatures increased; the lowest temperatures were, reached at approximately equivalent times in both hemispheres, presumably due to the importance of seasonal radiative forcing. Several local maxima (marked by arrows in Fig. 2) occurred in the minimum temperatures in both hemispheres; these correspond to minor warmings (of the "Canadian" type in the NH or "South Pacific" type in the SH) that commonly occur during fall and early winter [Farrara et al., 1992]. Near the end of January, the NH temperatures rose above the threshold for formation of PSCS due to the nearly major warming mentioned previously.

Figure 3 shows three-dimensional plots of the structure of the polar vortex throughout the stratosphere and of the region of potential PSC formation (as defined by NMC temperatures < 195 K) on equivalent days in both hemispheres. These plots are constructed by scaling Q by a standard-atmosphere value of $\partial\theta/\partial p$, the static stability, resulting in "vorticity units", as described by Dunker-ton and Delisi [1986] and Baldwin and Holton [1988].

The white surface in Fig. 3 shows the 1.9 s^{-1} contour of Q in these "vorticity units", a contour in the region of strong gradients of Q. The blue surface inside shows the region of temperatures < 195 K. The color-cd field at the bottom shows Q at 700 K, between the two levels discussed earlier; the 1.9 s^{-1} contour is at the border between green and blue in this field. The wintertime polar vortex formed first in the upper stratosphere, consistent with shorter radiative time constants there. While the polar vortex was approximately the same size and shape in the NH on 1 October as in the SH on 1 April, onc month later the vortex had already become broader in the SH, and was developing at lower altitudes. The vortex was, however, much more symmetric about the pole in the SH. in the NH during December and January, the polar vortex was obviously distorted and eroded by strong planetary wave activity, while the vortex remained quite symmetric in the SH during most of June and July.

It is evident in Fig. 3 that the region of very cold air was more extensive and persistent in the SH. Figure 4 shows the volume (within the region poleward of 30° latitude and from ≈200 to 5 hPa) where temperatures were less than 195, 190, and 185 K, as a function of time. The maximum volume covered by these low temperatures, and potentially by PSCs, in the SH was ≈ 3 times that in the Nil. The NH only occasionally became cold enough for the formation of Type 11 PSCs, while there was a large volume in the SH throughout late June and early July where Type 11 PSCs may have existed.

The two major forms of reactive chlorine produced in the presence of PSCS arc C1O and its dimer C1OOC1, which are linked by fast photochemical processes. Since only ClO is observed by the UARS MLS, we show in Fig. 5 plots as a function of altitude (pressure) and time of the area enclosed by the 195 K contour and which also received sunlight. This approximately defines the region where chlorine activated by PSCS will be in the form of C1O. It does not account for C1O advected to other areas or C1O produced by advection of C1OOC1, followed by photolysis or thermal decomposition.

The maximum area covered by the sunlit cold regions in theS11 was approximately twice as large as that in the NH, and occurred at somewhat higher altitudes. Lowest temperatures first appeared near 10 hPa in the NH and near 30 hPa in the SH, and extended downward as the year progressed, Near the end of the time period shown, temperatures began to increase, starting at higher altitudes.

conclusions

Comparison of the development of the stratospheric polar vortex during fall and early winter in the NH during 1991-1992 and in the SH during 1992 shows that temperatures in the SH fell below 195 K earlier and remained low longer than in the NH. The maximum volume of the region in the SH where PSCS may form was ≈ 3 times that in the NH. Although the distortion of the NH polar vortex puts more of this cold air in regions with sunlight, the area in the SH that both received sunlight and had minimum temperatures < 195K was ≈ 2 times as large as that in the NH, These interhemispheric differences are consistent with general features of the UARS MLS observations of C1O [Waters et al., 1993].

In 1991-1992 the polar vortex in the SH formed with less day-to-day variability and continued to deepen and expand longer than in the NH; there was considerable distortion and erosion of the NH polar vortex due to larger planetary-scale waves. Since there is considerably less interannual variability in fall and early winter than in late winter and spring [O'Neill and Pope, 1990], it is expected that the differences between the development of the wintertime stratospheric polar vortices in the NH and SH described here should be representative of typical interhemispheric differences.

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Figure Captions

Figure 1. Time series of the area within a given contour of the Rossby-Ertel potential vorticity (labeled with IQ I in units of 10^{-4} K $m^2kg^{-1}s^{-1}$) computed from NMC data in the NH (left column) and SH (right), at 840 K (top row) and 520 K (bottom). Area is normalized by the square of Earth's radius.

Figure 2. Daily minimum NMC temperatures on the 520 K isentropic surface and within the polar vortex, as defined by the 0.4 x 10-4 K $m^2kg^{-1}s^{-1}$ contour of IQ 1. Arrows indicate times of minor stratospheric warmings (see text).

Figure 3. Three-dimensional plots showing the development of the stratospheric polar vortex during fall and earl y winter in the NI I and SH. The white surface shows the 1.9 s^{-1} contour of $|Q|$ I in "vorticity units" (see text); the blue surface inside the white one shows temperatures < 195 K. The colored field at the bottom shows IQ I on the 700 K isentropic surface. latitude circles are shown at 40°, 60° and 80° N. or S.; E. longitudes 0° and 90° are labeled. The vertical coordinate is potential temperature θ, with 375 K $\leq$ $\theta \leq$ 1700 K.

Figure 4. Volume in the region from 30° to 90° latitude and $\approx$ 200 to 5 hPa in which temperatures are less than 195 (dark lines), 190, and 185 K (appeared only in the SI I).

Figure 5. Area as a function of altitude (pressure) of regions that both receive sunlight and have temperatures < 195 K, for the NI I (upper panel) for 1991-1992 and the SH (lower panel) for 1992. Contour intervals are 0.04 times the square of Earth's radius; the 0.16 -0.20 interval is shaded. Contour gaps are due to missing data.

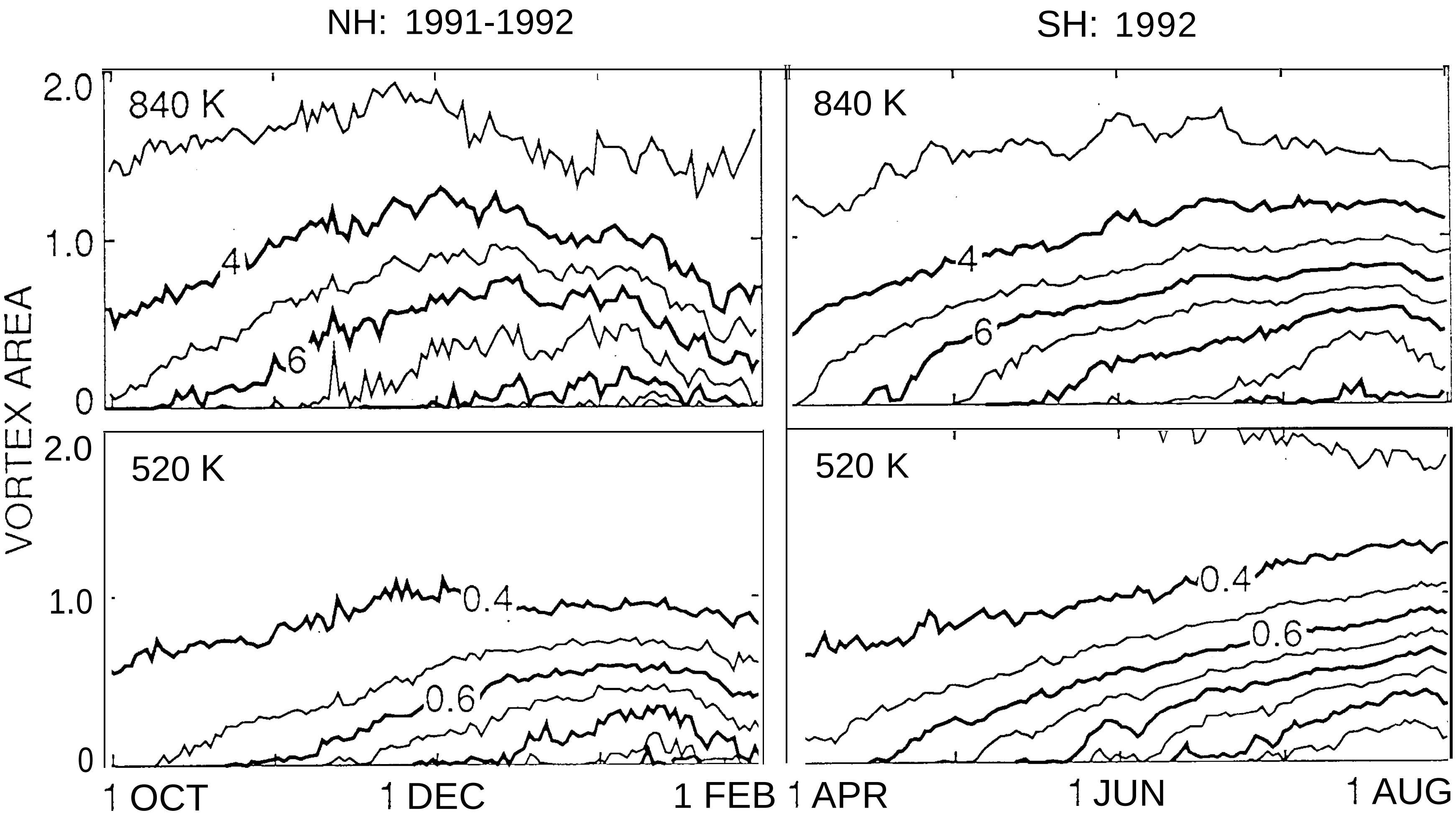

NH: 1991-1992
SH: 1992
VORTEX AREA
840 K
840 K
520 K
520 K
2.0
1.0
0
4
6
0.4
0.6
1 OCT
1 DEC
1 FEB
1 APR
1 JUN
1 AUG

FIGURE 1

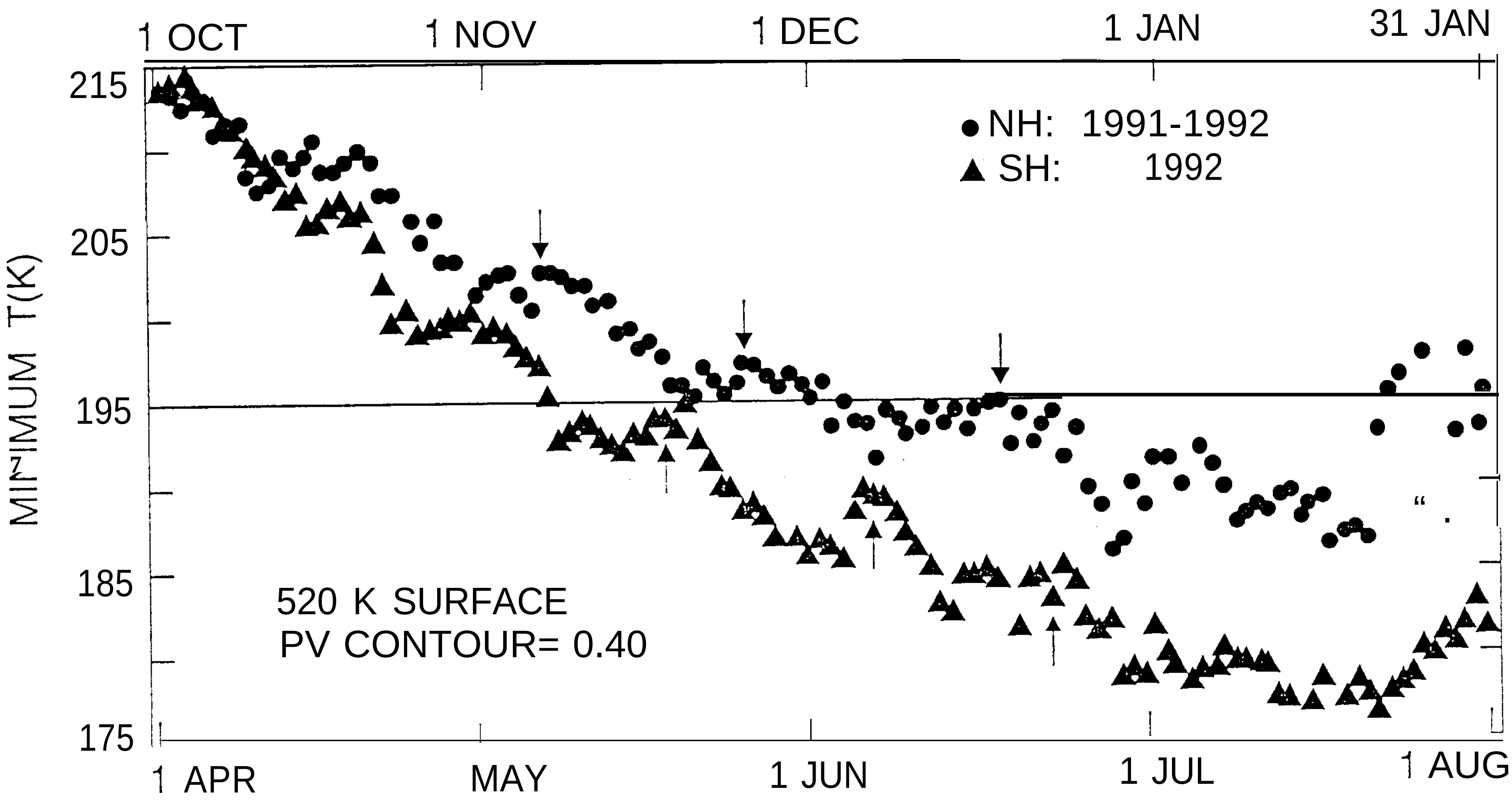
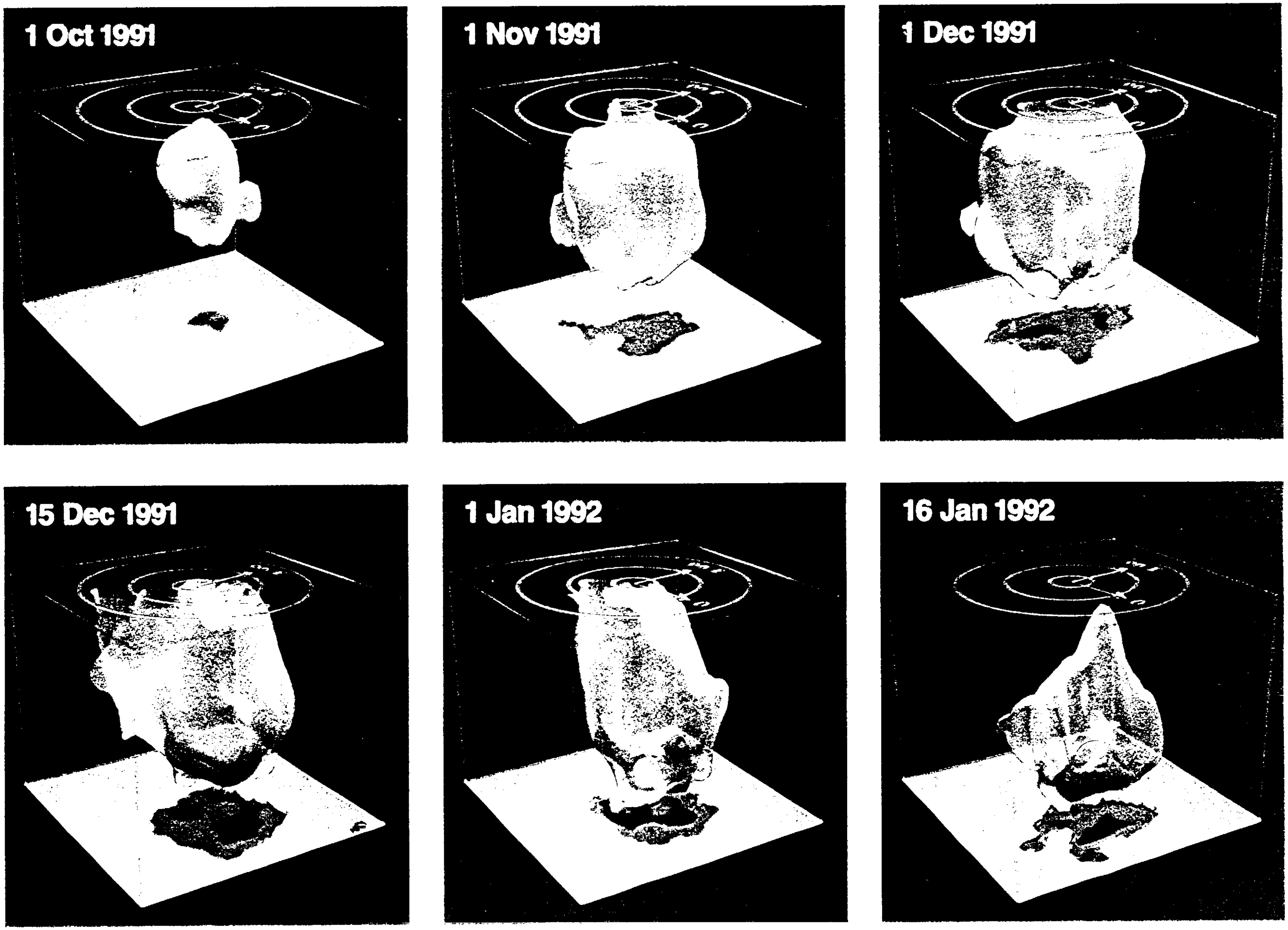
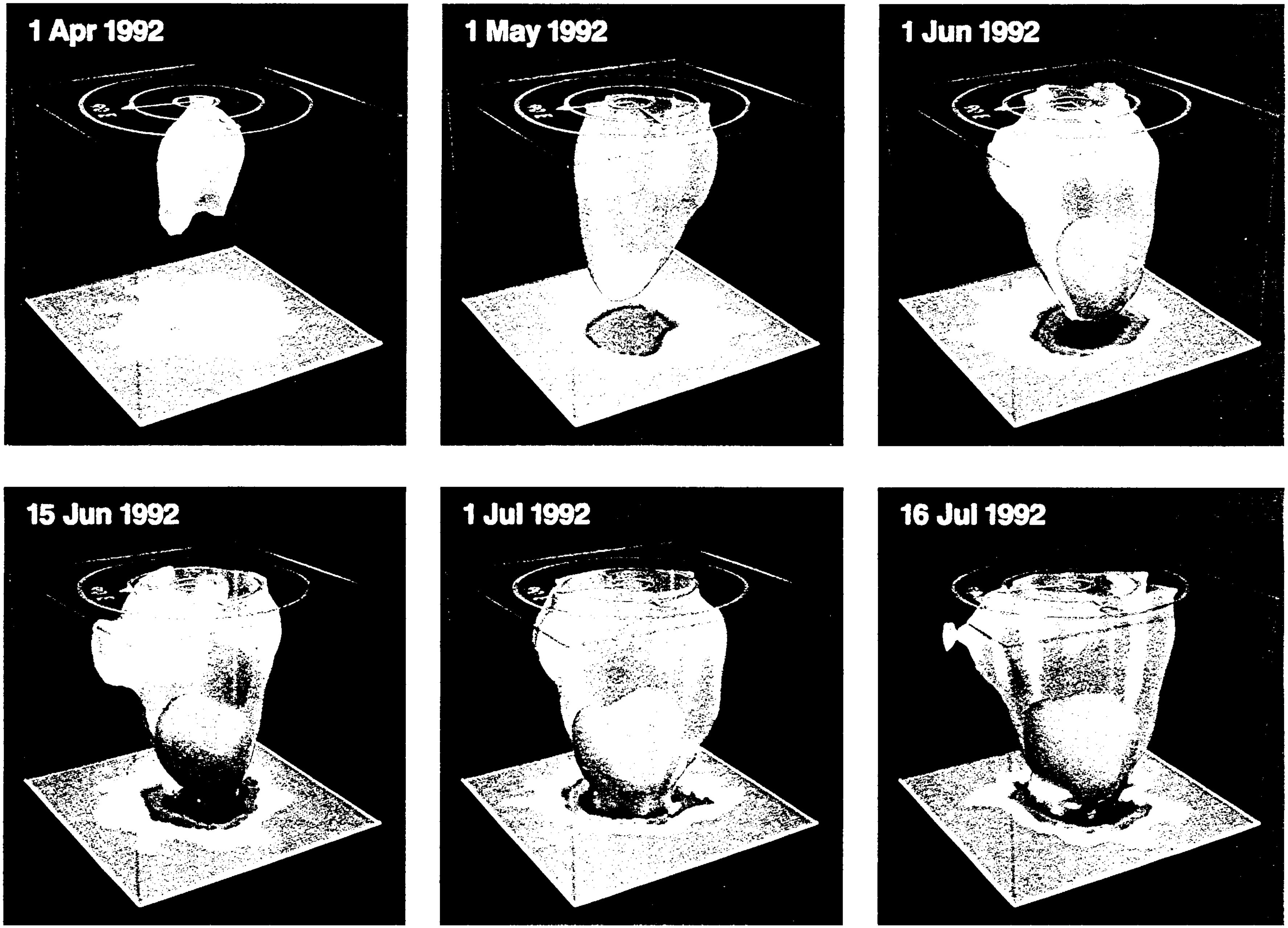

1 OCT
1 NOV
1 DEC
1 JAN
31 JAN
215
205
195
185
175
MINIMUM T(K)
NH: 1991-1992
SH: 1992
520 K SURFACE
PV CONTOUR= 0.40
1 APR
MAY
1 JUN
1 JUL
1 AUG

FIGURE 2


1 Oct 1991
1 Nov 1991
1 Dec 1991
15 Dec 1991
1 Jan 1992
16 Jan 1992


1 Apr 1992
1 May 1992
1 Jun 1992
15 Jun 1992
1 Jul 1992
16 Jul 1992

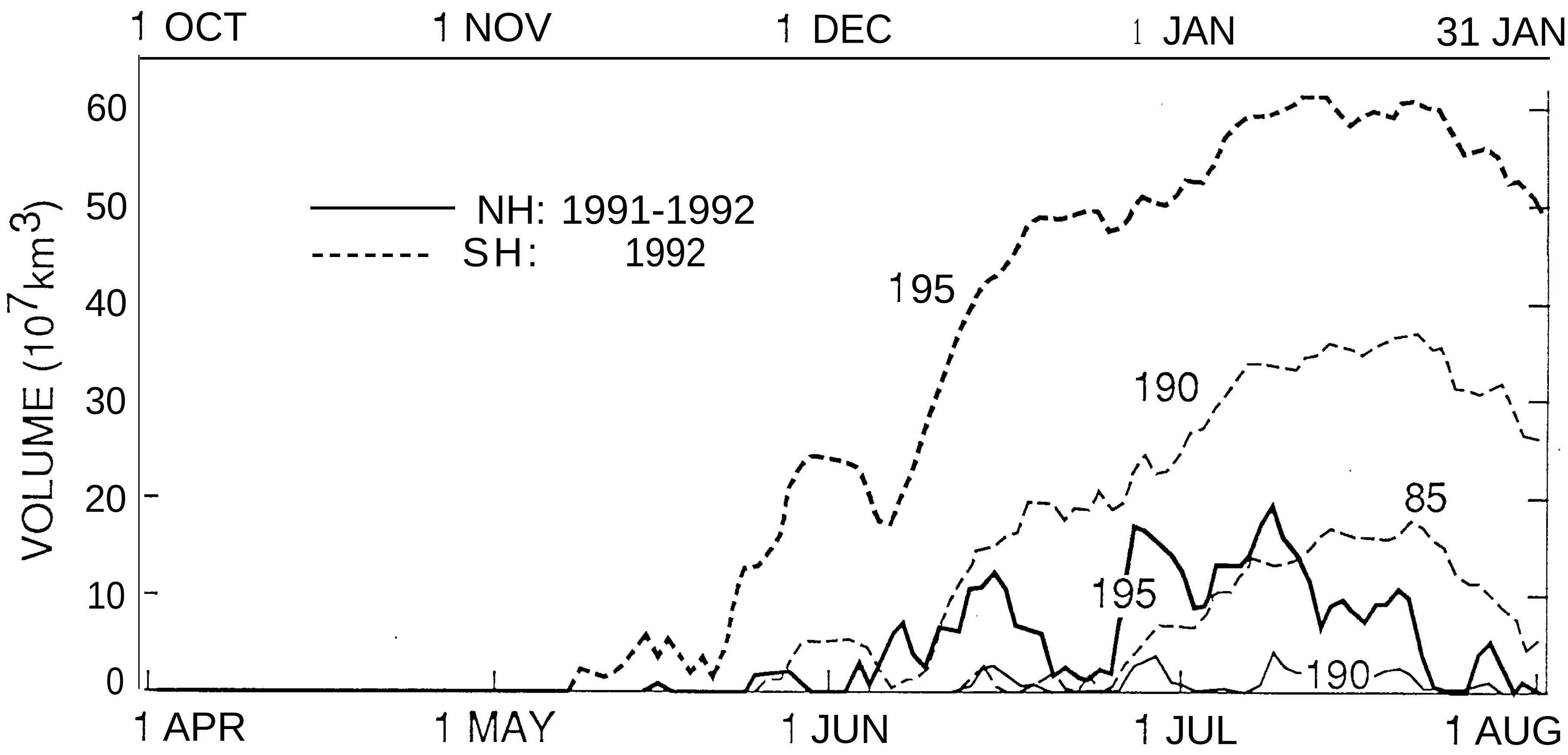

1 OCT
1 NOV
1 DEC
1 JAN
31 JAN
60
50
40
30
20
10
0
VOLUME (10^7km^3)
NH: 1991-1992
SH: 1992
195
190
85
195
190
1 APR
1 MAY
1 JUN
1 JUL
1 AUG

FIGURE 4